SubMM Wave Superconducting Hot-Electron Direct Detectors

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Objective & Approach

The objective is to develop a submillimeter detector with an **NEP≈10^{-20} W/Hz$^{1/2}$** and a time constant $\tau \approx$ **0.1 ms**, and large-array scalability for future space telescopes.

The approach is to use a **hot-electron effect in transition-edge sensors** made from disordered superconducting films (Ref's 1&2).

Hot-**E**lectron **D**irect **D**etector (**HEDD**) features:

- High sensitivity **NEP≈10^{-20} W/Hz$^{1/2}$ @ 0.1 K, NEP≈10^{-18} W/ Hz$^{1/2}$ @ 0.3 K**
- Small size (~1×1×0.01 μm^3); suitable for coupling to a planar antenna
- Bulk substrate (Si, sapphire); no thin membranes required
- Fast response $\tau \approx$ **0.1 ms @ 0.1 K,** $\tau \approx$ **1 μs @ 0.3 K**
- Integration with planar antenna (rf impedance ~ 20-100 Ω)
- SQUID read-out

Issues addressed in this work

1. Low NEP relies on small device volume and long intrinsic (electron-phonon) relaxation time $\tau_{e\text{-}ph} \approx 1$ ms. **Disordered** superconducting films should be used since τ_{e-ph} **increases** with decreasing of temperature and increasing of **concentration of defects** at T<1 K (Ref's 3-6).

   Suitable materials have been identified and synthesized and $\tau_{e\text{-}ph}$ has been measured.

2. The diffusion length of quasiparticles at 0.1 K is much longer than the device length, so Andreev contacts should be used to prevent the escape of "hot" quasiparticles. The quasiparticles with energy above the gap in the contacts, $\Delta_{contact}$, may, in principle, **diffuse out before they relax** to the energy gap, and recombine in the contacts. In this case, a part of the signal energy will be lost in 2Δ phonons, which will not contribute to the change of the bolometer resistance. The effect would have a spectral threshold at $\nu = \Delta_{contact}/h$.

   The spectral response of a 1-μm-long microbridge has been measured.

3. *1-3 μm-long Ti bridges were fabricated from a 20 nm thick film (T_c = 0.3-0.36 K).*

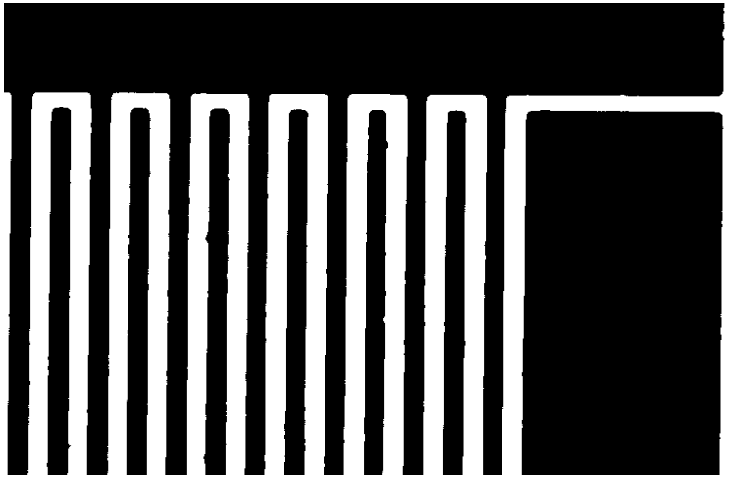
4. *Output noise spectra have been measured and compared with the theoretical predictions.*

Electron-phonon time measurements in Hf and Ti

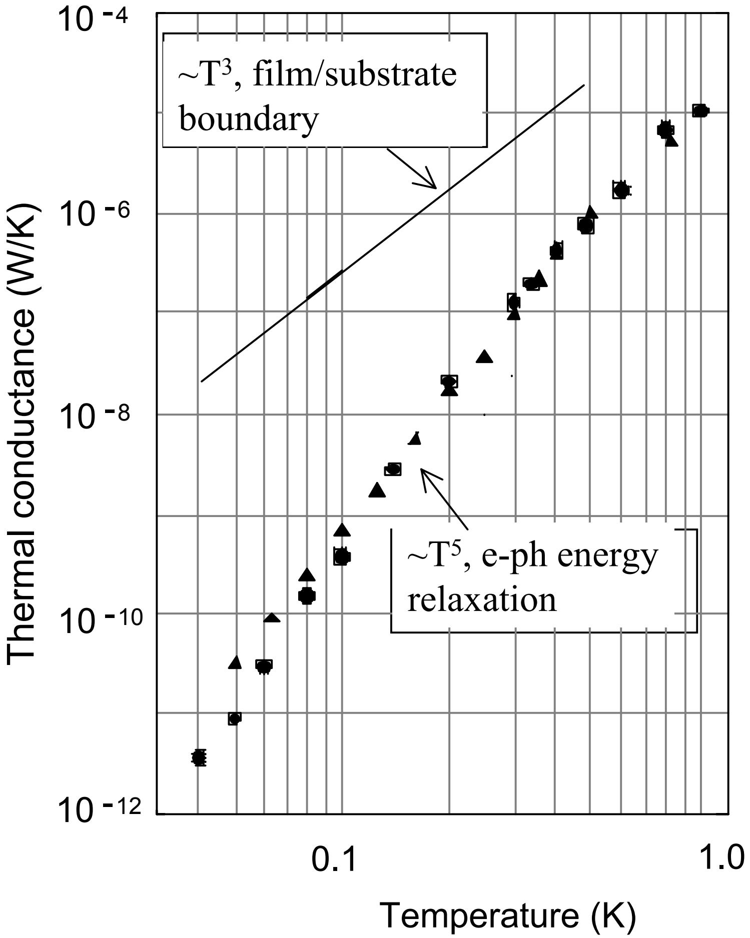
Magnetron sputtered films on sapphire substrates

Hf
d = 25 nm
$R_\square = 38\ \Omega$
$T_c = 0.3\text{-}0.48$ K
$D = 1.5\ cm^2/s$

Ti
d = 20 nm
$R_\square = 15\ \Omega$
$T_c = 0.43$ K
$D = 2.5\ cm^2/s$

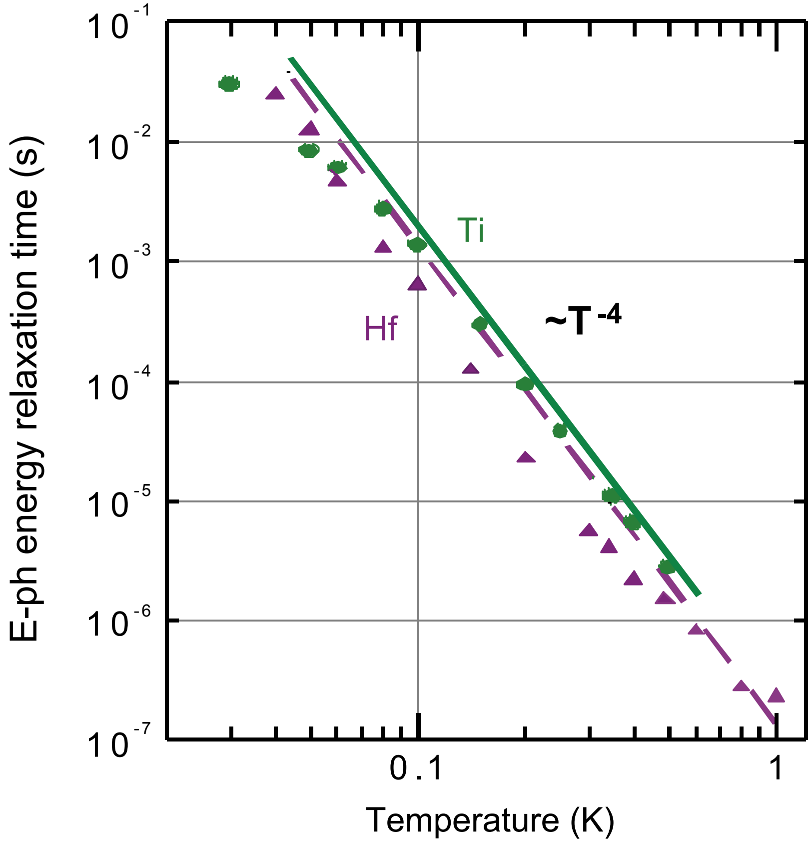


Microphotograph shows a portion of the meander-type structure used for measurements of the electron-phonon thermal conductance. The width of the strip is 5 μm, the total length is 10 cm.



The e-ph thermal conductance is orders of magnitude weaker than that of the film/substrate interface. The T^5 temperature dependence of $G_{e\text{-}ph}$ implies a T^{-4} dependence of the relaxation time ($\tau_{e-ph}=C_e/G_{e\text{-}ph}$)

Electron-phonon time measurements in Hf and Ti (cont.)



Lines are the calculations using Electron-Phonon-Impurity Interference theory by Sergeev&Reizer with no free parameters

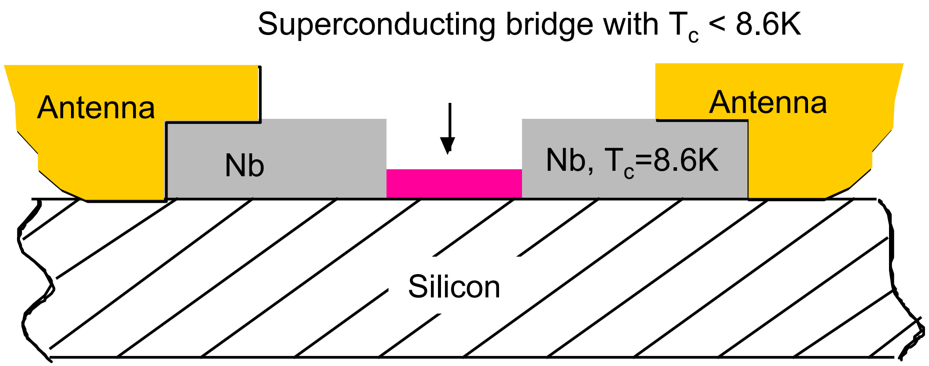
- With the films diffusivity D=1-2 cm^2/s the 1 μm length would be long enough to avoid deterioration of the TES properties due to the proximity effect from Nb contacts.

- The detector response time constant would be ~10 times shorter than the intrinsic $\tau_{e\text{-}ph}$ due to the negative Electro-Thermal Feedback typical for a TES.

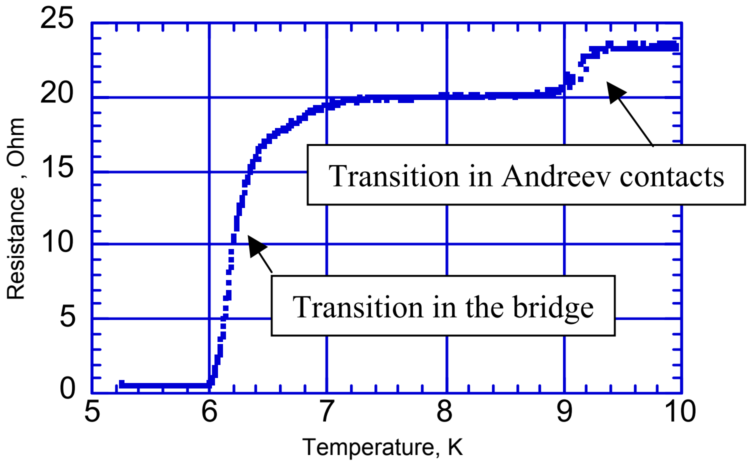
- At 0.1 K, a 1×1 μm^2 size HEDD would exhibit an $NEP=(4k_BT^2C_e/\tau_{e\text{-}ph})^{1/2} \sim 10^{-20}$ W/√Hz due to intrinsic thermal fluctuation noise. At 0.3 K, the NEP ~ 10^{-18} W/√Hz.

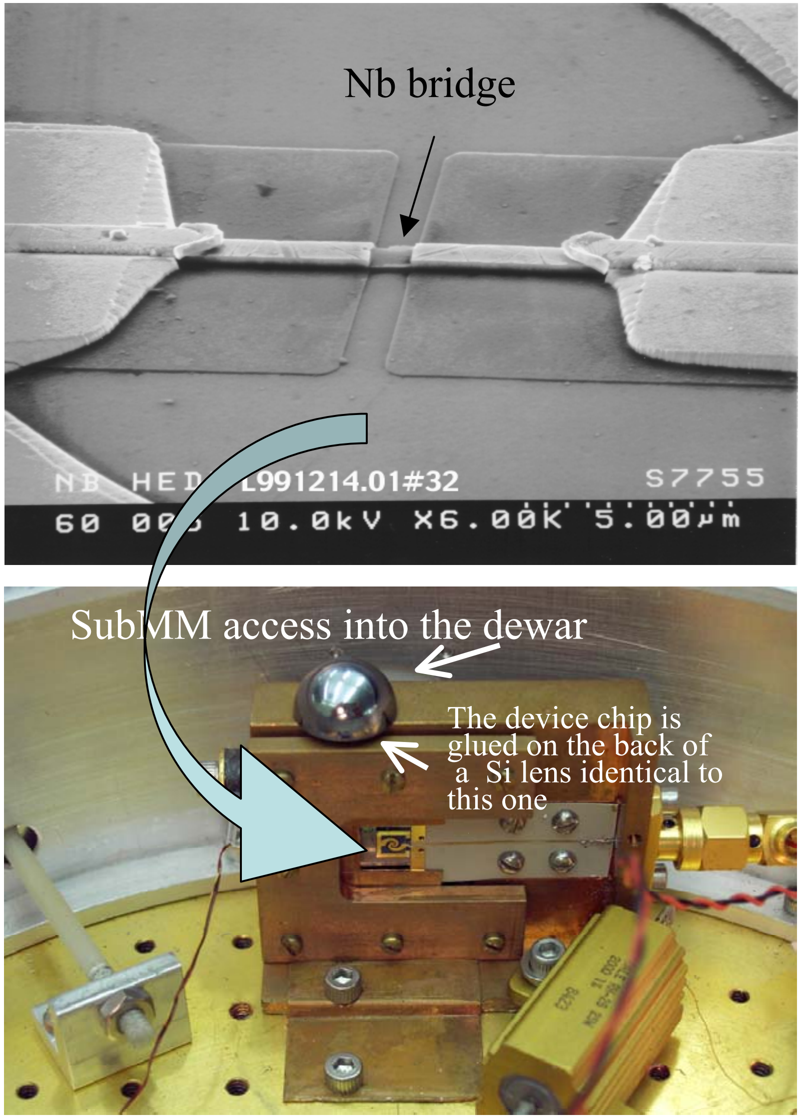
(See Ref's 3-4 for more details on these measurements)

Submillimeter spectral response of Nb HEDD



1-µm long devices made from a magnetron sputtered 12 nm thick Nb film on Si with 150 nm Nb Andreev contacts and Au spiral antenna were used to **model** the spectral behavior of low-T_c HEDDs. The length is **minimum** to avoid the proximity effect at **0.1 K**. The bridge length, L, satisfies the requirement: $L \gg (D\tau_{ee})^{1/2}$ for thermal quasiparticles. However, this non-equality may break for $h\nu \gg \Delta_{Nb}$.

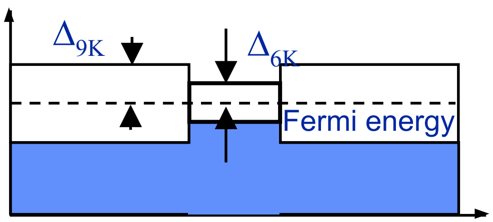




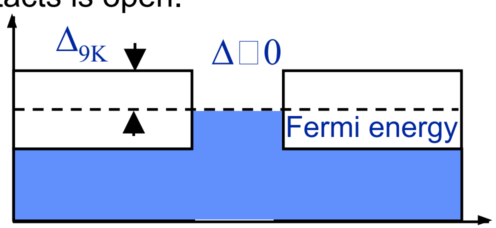
Spectral response (cont.)

The quasiparticles excited near the edge of the bridge may not have enough time to relax to energies below $\Delta_{contact}$. If they diffuse into the contact area their energy can be lost via recombination and emission of 2Δ-phonons. To verify that, the spectral response was measured in three regimes:

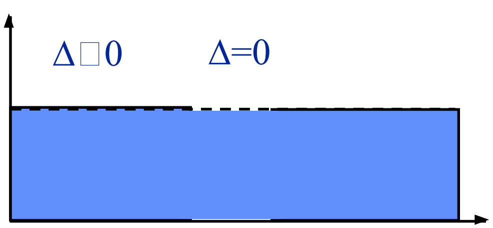
(1) T= 4.2 K, “low” bias. Both the energy gap in the device and the gap in the contacts are open.

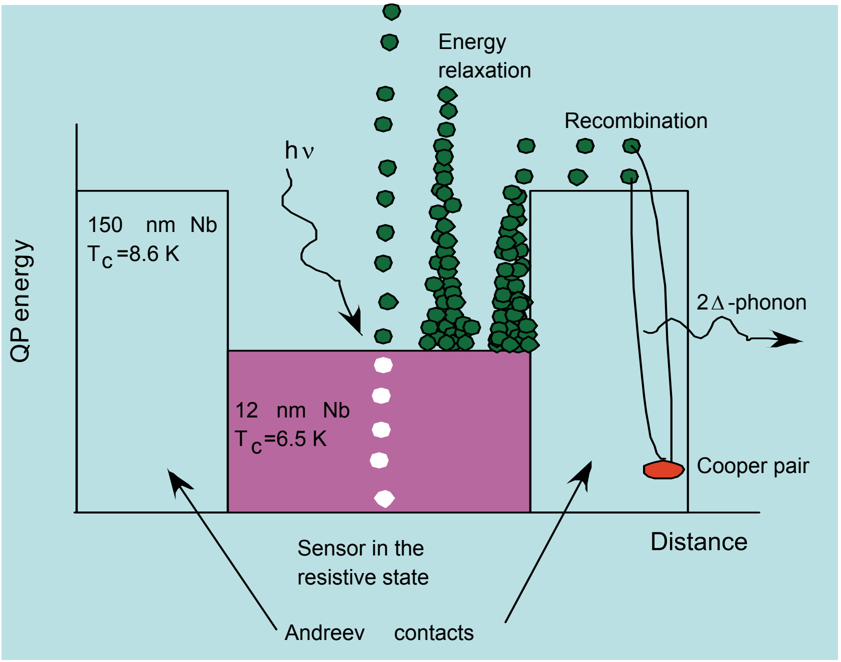


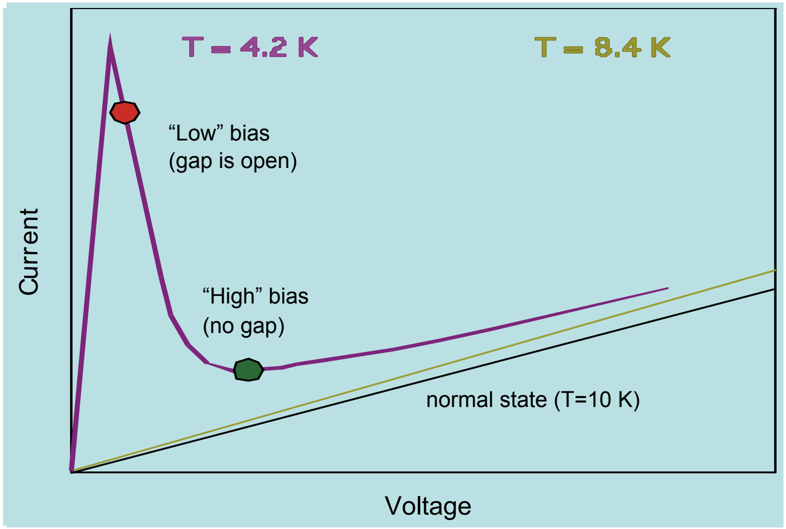
(2) T=4.2 K, “high” bias. The gap in the device is closed, the gap in the contacts is open.



(3) T=8.4 K, both gaps are closed



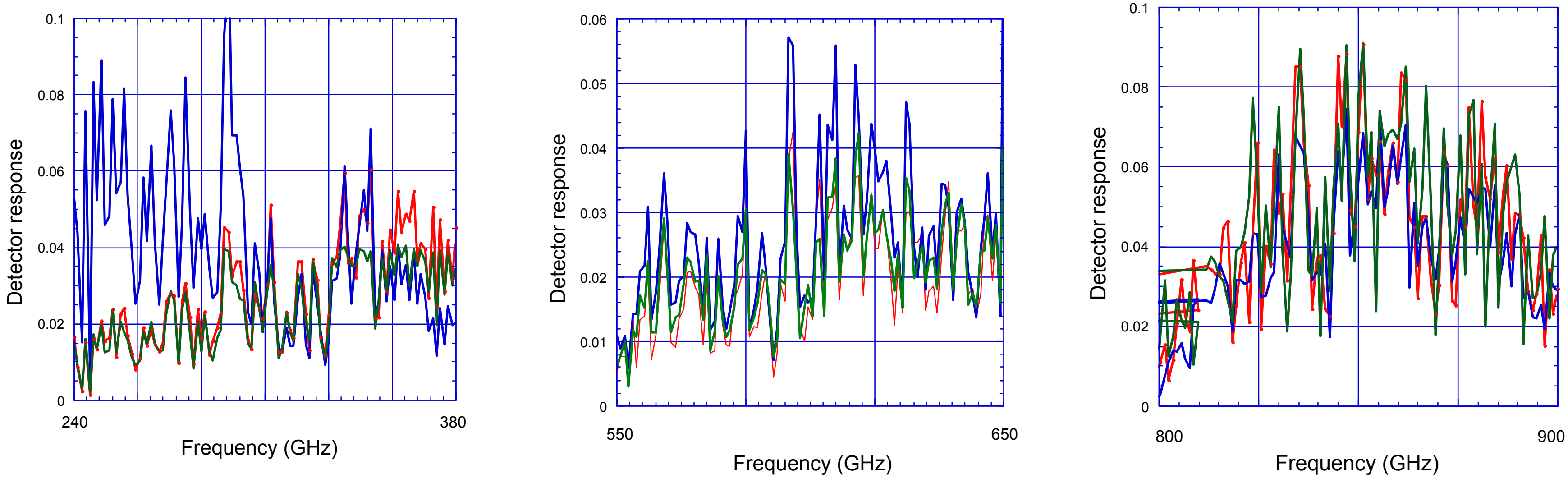




Spectral response (cont.)

By comparison of cases (2) and (3) one can extract a normalized absorption spectrum in the microbridge. The spectrum for case (1) reflects the frequency dependence of the surface impedance of the bridge. Above the frequency $f_0=2\Delta_{bridge}/h$ case (1) coincides with case (2). Three SubMM BWOs were used to cover the 260-990 GHz range. This range includes the energy gaps in both thick Nb contacts and thin Nb film.

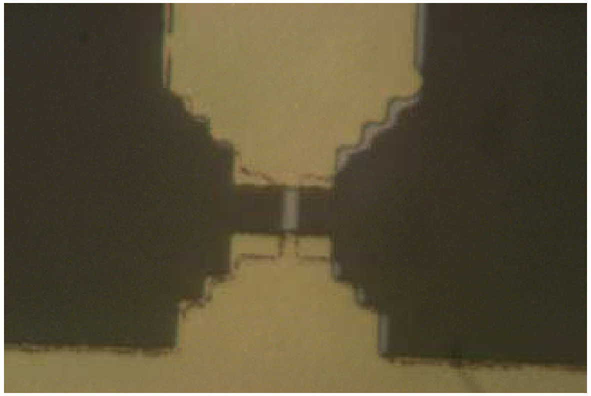
Lines: blue - case (1) 4.2K, “low” bias; red - case (2) 4.2K, “high” bias; green - case (3) 8.4 K.



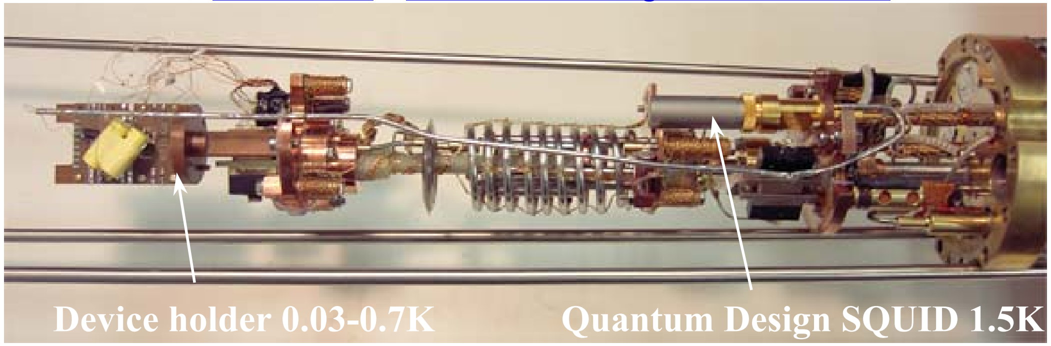
- The energy relaxation length of hot electrons with energy $\Delta_{contact}$ is 0.1 μm (ie: 10 times shorter than the device length). However, much smaller fraction of electrons may diffuse to the contacts since the electron energy distribution is practically exponential
- The experiment confirms that there is no noticeable decrease of the response above the frequency $\Delta_{contact}/h$
- Since the potential spectral effect would depend only on $\Delta_{contact}$ and on the diffusion constant D, the results apply to Hf/Ti HEDDs. The latter have the diffusivity value similar to that in Nb thin film and $\Delta_{contact}$ at 4.2 K is the same as that at subkelvin temperatures.

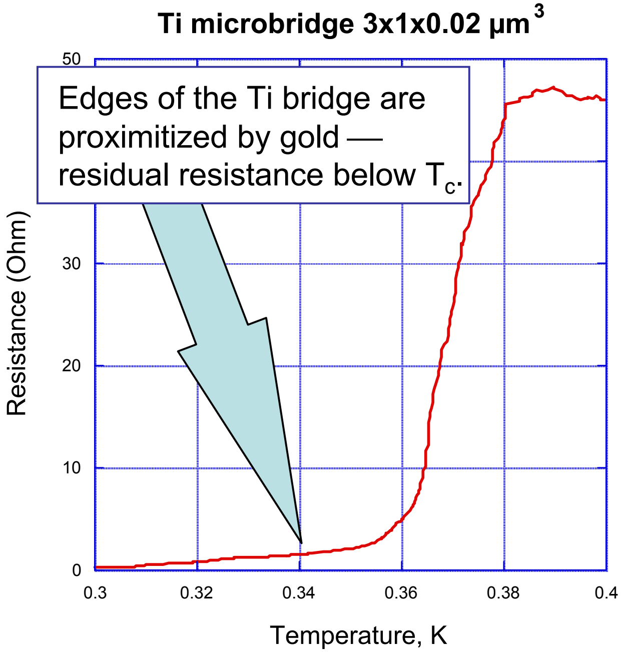
Ti microbolometer fabrication and characterization

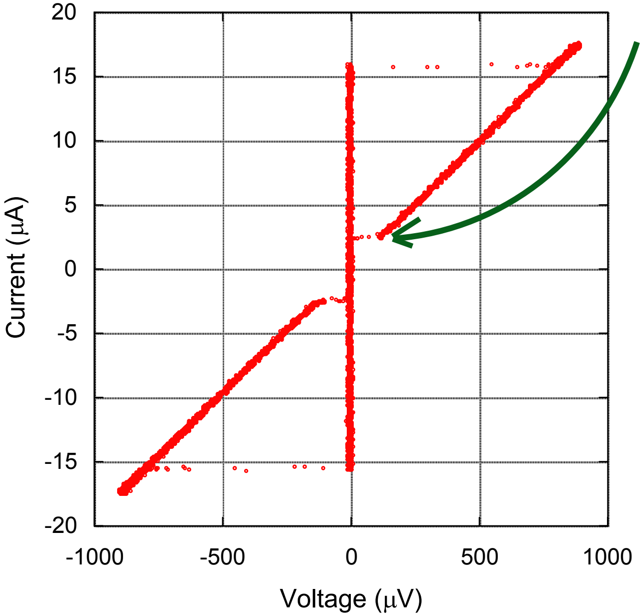
As the first step in fabrication of a practical HEDD, 1-3 μm-long bridges were fabricated from 20 nm thick Ti film. The contacts were made from gold: no Andreev contacts yet.



Kelvinox[25] dilution refrigerator insert



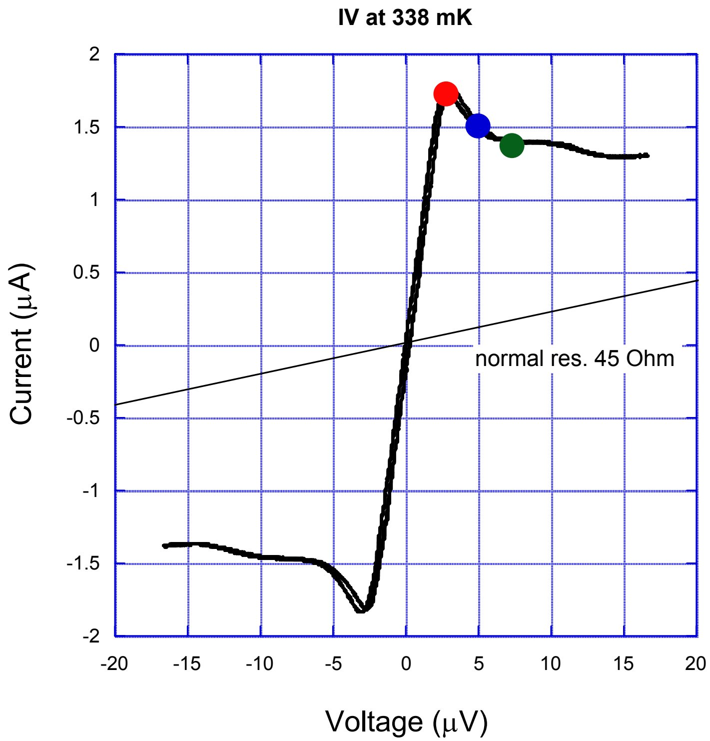




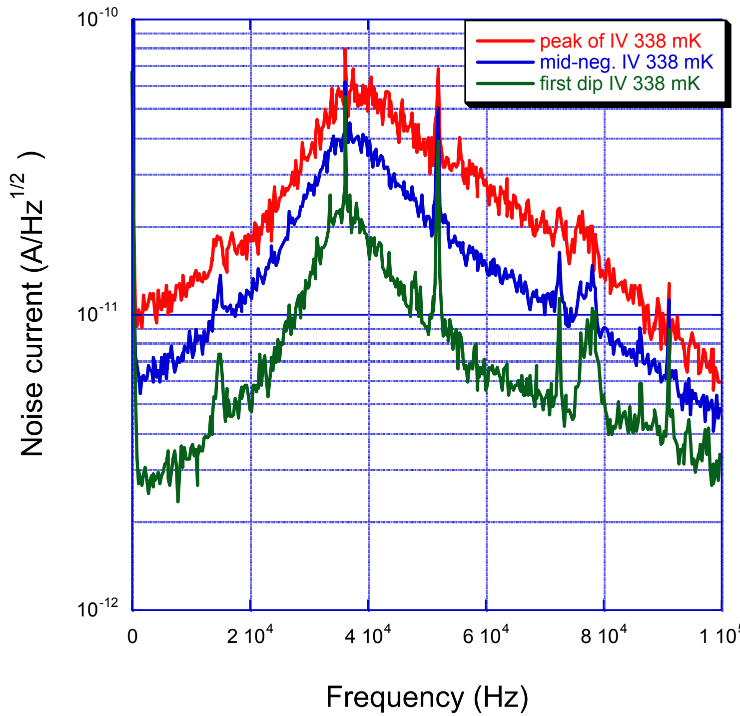
From the **current drop back point,** the effective thermal conductance was determined assuming the electron temperature at this point is equal to T_c. The thermal conductance corresponds to that for the electron diffusion via the bridge ends. The corresponding electron temperature relaxation time is ≈ **10 ns**. Incorporation of Andreev contacts should increase this time to the electron-phonon value which would be ≈ **10 μs**.

Noise measurements

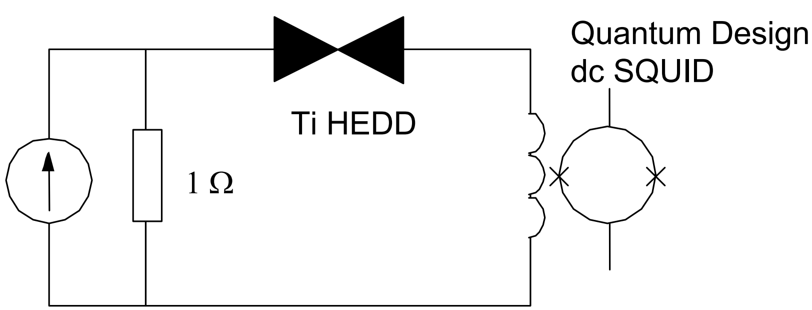
Positions of the bias points in noise measurements



Noise spectra for a 3-μm-long Ti bridge at 338 mK

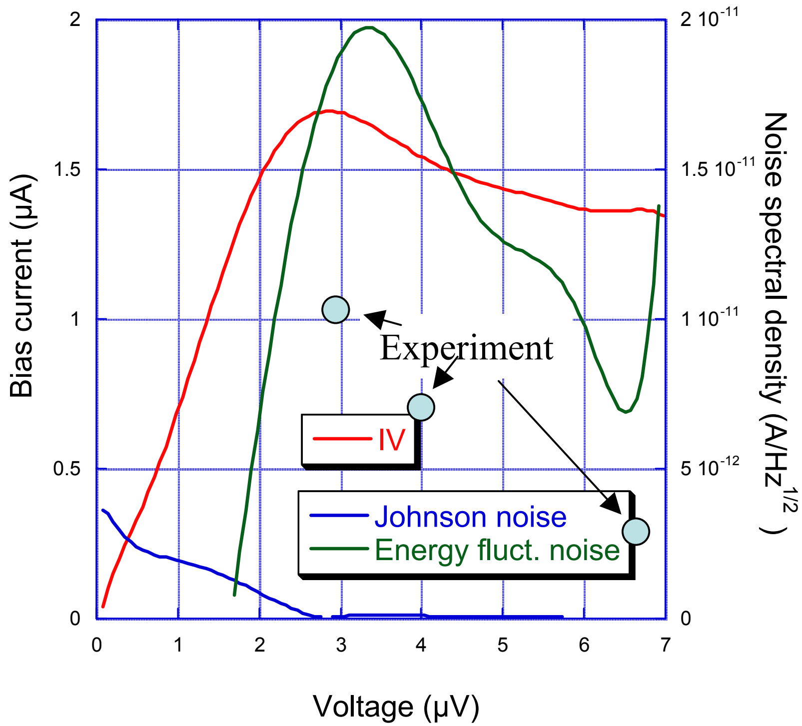


Schematic electrical circuit



- The behavior of the noise at **zero frequency** for 3 different bias voltages correlates with that for the thermal energy fluctuation noise.
- There is practically no change in the spectral variation of the noise which can be explained by a very short electron temperature relaxation time (the effective cut-off frequency for a bare relaxation time would be ≈ 16 MHz).
- The resonance is due to the SQUID circuit and electronics.

Modeling of the output noise



The NEP ≈10^{-16} W/Hz$^{1/2}$ can be derived from these data

Electron energy fluctuation noise and Johnson noise were calculated from an experimental IV characteristic assuming the latter is fully defined by self-heating effects

- The self-heating parameter ("ETF loop gain") was found as **C**=[(dV/dI)-R]/[(dV/dI)+R]
- The responsivity was found as S_I = (**C**/V) /(1+**C**)
- The output noise due to electron energy fluctuations is $S_{ef} = (4k_BT_eC_e/\tau_{diff.})^{1/2} \times S_I$
- The output Johnson noise is $S_J = (4k_BT_e/R)^{1/2}/(1+\mathbf{C})$

C_e is the electron heat capacity, R=V/I, $\tau_{diff.}$ is the electron diffusion time

Modeling agrees well with the noise data (calculated values are only within a factor of two higher than the experimental values). This discrepancy will be addressed in the future. The hot-electron model for a diffusion-cooled HEDD thus provides a good framework for modeling these detectors.

Summary

1. Low-T_c disordered superconducting materials with very weak e-ph interaction (Hf/Ti) have been identified. The material parameters are suitable for achieving the desired sensitivity and speed in the HEDD at 0.3 K. More work is needed to adjust T_c for 0.1 K operation.
2. The diffusion of high-energy quasiparticles into Andreev contacts in a 1-μm-long HEDD is insignificant and does not cause decrease of the sensitivity at frequencies up to 1 THz.
3. Micron-size Ti detector devices have been fabricated and tested. The overall performance including the output noise agrees with expectations based on hot-electron mechanism with diffusion cooling of electrons.
4. Ti devices with Nb Andreev contacts are being fabricated.
5. After proving the detector concept on prototype devices (output noise and speed), an antenna coupled Ti HEDD will be fabricated and the optical NEP will be measured.

Acknowledgment

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Publications

1. B.S. Karasik, W.R. McGrath, H.G. LeDuc, and M.E. Gershenson, "A Hot-Electron Direct Detector for Radioastronomy", *Superconductor: Science & Technology,* **12**, pp.745-747 (1999*).*
2. B.S. Karasik, W.R. McGrath, M.E. Gershenson, and A.V. Sergeev, "Hot-Electron Detector with Disorder-Controlled Time Constant", *Journal of Applied Physics* **87**(10), pp.7586-7588 (2000).
3. M.E. Gershenson, D. Gong, T. Sato, B.S. Karasik, W.R. McGrath, and A.V. Sergeev, "Hot-electron direct detectors: towards record sensitivity via disorder-suppressed electron-phonon coupling", *Proc. 11th Int. Symp. on Space Terahertz Technology*, May 1-3, 2000, University of Michigan, Ann Arbor, MI, pp.514-523.
4. M.E. Gershenson, D. Gong, T. Sato, B.S. Karasik, and A.V. Sergeev, "Millisecond Electron-Phonon Relaxation in Ultrathin Disordered Metal Films at Millikelvin Temperatures", *Applied Physics Letters* **79**(13), pp. 2049-2051 (2001).
5. A. Sergeev, B.S. Karasik, M. Gershenson, and V. Mitin, "Electron-Phonon Scattering in Disordered Metallic Films," *Physica B* (2002), in press.
6. B.S. Karasik, A.V. Sergeev, and M.E. Gershenson, "Electron-Phonon Relaxation in Hot-Electron Detectors below 1 K", *Low Temperature Detectors*-Proc. 9th Int. Workshop on Low Temperature Detectors, Madison, WI, 2001, AIP Conf. Proc 605, pp. 75-78.